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# Monitoring Beach Changes Using GPS Surveying Techniques

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## ABSTRACT

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A need exists for frequent and prompt updating of shoreline positions, rates of shoreline movement, and volumetric nearshore changes. To effectively monitor and predict these beach changes, accurate measurements of beach morphology incorporating both shore-parallel and shore-normal transects are required. Although it is possible to monitor beach dynamics using land-based surveying methods, it is generally not practical to collect data of sufficient density and resolution to satisfy a three-dimensional beach-change model of long segments of the coast. The challenge to coastal scientists is to devise new beach monitoring methods that address these needs and are rapid, reliable, relatively inexpensive, and maintain or improve measurement accuracy.

The adaptation of Global Positioning System (GPS) surveying techniques to beach monitoring activities is a promising response to this challenge. An experiment that employed both GPS and conventional beach surveying was conducted, and a new beach monitoring method employing kinematic GPS surveys was devised. This new method involves the collection of precise shore-parallel and shore-normal GPS positions from a moving vehicle so that an accurate two-dimensional beach surface can be generated. Results show that the GPS measurements agree with conventional shore-normal surveys at the 1 cm level, and repeated GPS measurements employing the moving vehicle demonstrate a precision of better than 1 cm. In addition, the nearly continuous sampling and increased resolution provided by the GPS surveying technique reveals alongshore changes in beach morphology that are undetected by conventional shore-normal profiles. The application of GPS surveying techniques combined with the refinement of appropriate methods for data collection and analysis provides a better understanding of beach changes, sediment transport, and storm impacts.

**ADDITIONAL INDEX WORDS:** *Shoreline change analysis, three-dimensional beach models, storm impact assessment, beach profiles.*

## INTRODUCTION

Coastal erosion and deposition are three-dimensional phenomena that are usually inferred from changes in one-dimensional data such as shoreline position (map view) or changes in features on a beach profile (cross-section view). Beach monitoring provides a way of understanding beach dynamics and the factors that influence volumetric gains and losses along the coast. Beach monitoring also can reveal short-term trends in beach stability and rates of shoreline movement, which potentially can be incorporated in mathematical models to predict shoreline positions. Until recently, field monitoring of dynamic coastal environments has been difficult because large spatial scales tended to limit the number of beach segments that could be surveyed efficiently, and therefore an integrated depiction of the entire beach surface over long distances has been incomplete.

Predicting future rates of coastal erosion and land loss has progressed from a purely academic exercise to one of environmental importance as many coastal states and government agencies rely on technical data to determine construction setback lines and insurance hazard zones (NATIONAL RESEARCH COUNCIL, 1990). To support these public policies some coastal states (Florida, North Carolina, South Carolina) have established elaborate networks of closely spaced beach profile monuments that are periodically revisited to assess magnitudes and rates of shoreline movement. In turn, the rates of shoreline movement are used to establish building zones and to create construction control lines. Currently the Federal Emergency Management Agency (FEMA) is recommending legislation that would establish hazard

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zones based on 10, 30, and 60 times the annual erosion rate (NATIONAL RESEARCH COUNCIL, 1990). Thus, accurately interpreting trends of shoreline movement and precisely quantifying the rates of movement are necessary to accurately predict future shoreline positions.

Beach profiles oriented perpendicular to the shoreline (Figure 1) can be obtained with various types of equipment ranging from simple graduated rods and chains (EMERY, 1961), to standard stadia rod and level, to a more accurate autotracking geodimeter with a reflecting prism (BIRKEMEIER *et al.*, 1991). The more sophisticated techniques offer greater measuring precision, but they also require more field support and data processing equipment, such as computers and specialized software.

A typical shore-normal beach survey yields a one-dimensional profile that represents the relative height of the beach from a fixed reference marker. This profile also displays the position of particular beach features, such as shoreline, berm, dunes, vegetation line, or a datum intercept such as the National Geodetic Vertical Datum (NGVD). Comparison of subsequent beach surveys yields a two-dimensional cross-sectional area, which represents the amount of beach erosion and deposition that occurred between surveys. A three-dimensional volumetric change in the beach is derived from the profiles by integrating between adjacent cross-sectional areas.

There are three potentially large errors associated with these approaches to estimating beach erosion or deposition. The first is that all of the measurements are made relative to a fixed monument. If this marker is lost or damaged, accurate comparison of previous surveys with subsequent surveys would be extremely difficult. The second potential error occurs if subsequent surveys do not follow the same course (compass bearing) as the previous survey. The third potential error involves the three-dimensional interpolation from two-dimensional data. Interpolated results are subject to significant errors if the two-dimensional comparisons neglect subtle changes in the beach surface or if the adjacent profiles are widely spaced.

Practical limitations associated with conventional beach monitoring are (1) the long time required to conduct extensive surveys, (2) the common loss of "permanent" monuments where the beach is either rapidly eroding or subjected to substantial wave penetration during storms, and (3) the aforementioned errors associated with estimating volumetric changes from inadequate data. Estimates of volumetric beach changes can be significantly improved if the beach is surveyed by an intersecting grid of profiles oriented both perpendicular and parallel to the shoreline (Figure 2). By providing a more accurate representation of the actual beach surface, a grid of profiles can reduce the error that currently is introduced when unknown elevation changes between profiles are ignored or estimated by interpolation.

To overcome existing field limitations, new beach monitoring techniques are needed that are rapid, as accurate as conventional surveys, independent of site-specific monuments, and that integrate most of the beach surface so that two-dimensional representations closely approximate actual conditions. Surveying methods that employ global positioning system (GPS) technology are emerging as likely solutions to this dilemma because they can provide extremely accurate locations (latitude, longitude, height) of remote sites with a minimum of field operation time. In addition, GPS surveys conducted from vehicles can provide synoptic two-dimensional representations of long beach segments, an accomplishment that is not easily achieved using traditional surveying equipment such as theodolite and stadia rod or electronic surveying equipment such as total stations.

## GPS OVERVIEW

GPS is a satellite-based positioning system developed by the U.S. Department of Defense (DoD) to provide continuous, worldwide, all-weather navigation primarily for military users. There are a variety of approaches for utilizing GPS, but the basic positioning concept can be thought of as triangulation with satellites as ranging sources.

From the user's perspective, the GPS satellites provide three kinds of information: the broadcast ephemeris, the pseudorange, and the carrier phase. The broadcast ephemeris provides users with the satellite position information. The pseudorange provides a direct measurement of the satellite-to-receiver distance, but it is biased by the clock error in the user's receiver (hence pseudorange). The carrier phase measurement is the difference between the phase of the incoming carrier wave and the phase of the reference signal generated by the GPS receiver.

A receiver tracking four or more satellites can solve for a three-dimensional position (latitude, longitude, altitude) and also for the GPS receiver clock bias using the pseudorange and broadcast ephemeris. The accuracy of the computed position depends on the accuracy of the broadcast ephemeris and pseudorange. Even greater positioning accuracy can be achieved by employing the carrier phase measurement. The carrier phase data is one to two orders of magnitude more precise than the pseudorange and it provides a very precise measurement of the change in range to the satellite. For this reason the carrier phase is the primary observation used for surveying and precise positioning.

There are two levels of real-time accuracy provided by GPS: the Standard Positioning Service (SPS) provides 100 meter accuracy, whereas the Precise Positioning Service (PPS) provides 16 m accuracy. There are no restrictions on access to the SPS, but the PPS is only available to the DoD and other selected users. The PPS accuracy is degraded to SPS levels by implementation of Selective Availability (SA). SA is the deliberate corruption of the clock and orbit information broadcast by the satellites so that positions obtained by single (autonomous) receivers are less accurate.

Users that require greater accuracy than an autonomous system provides typically employ a differential mode that negates the effects of SA. Differential GPS is a data collection and processing technique in which two or more receivers track the same satellites simultaneously. One receiver is located over a known reference point and the position of an unknown point (platform, survey mark, sensor) is determined relative to the reference point. Because the errors in GPS positioning (satellite clock and orbit errors, along with SA effects) are essentially the same within a limited area (500 km radius), the errors can be calculated and corrected using the differential technique. This allows differential position accuracy to far exceed the normal GPS system accuracy that relies on a single receiver operating autonomously. Differential GPS users are able to determine the position of dynamic platforms (vehicles, vessels, and aircraft) at the few meter level in real time and at the centimeter level in post-processing. Accuracies of 0.5 cm plus one to two parts-per-million (ppm) of the baseline length are routine, and specialized analyses can result in improvement of one or even two orders of magnitude. The accuracies achievable using differential GPS have allowed GPS technology to be successfully employed in a number of other applications including surveying and geodesy, photogrammetric mapping, hydrography, gravimetry, and crustal motion studies.

## KINEMATIC GPS SURVEYING METHODS

Kinematic GPS surveys involve collecting data while the antenna of the mobile receiver is moving. The movement of the antenna can be intermittent (stop-and-go) or continuous (fully kinematic). For stop-and-go kinematic surveys, the user is typically on land and interested in rapid surveys of a series of stationary points. The operational scenario involves stopping over a survey point long enough to employ averaging to reduce random errors and then going on to the next point. Typically a few minutes of data collection at each point is sufficient. Stop-and-go kinematic surveys and conventional surveying techniques that employ theodolite and stadia rod or total stations are similar because all of these techniques collect static data at a series of discrete points. Differential fully kinematic GPS surveys are designed for rapid, centimeter level positioning on continuously moving platforms (vehicles, planes, and boats) where the vehicle path or platform trajectory is of interest. For fully kinematic surveys, an independent position is computed each time the mobile receiver obtains a fix. The density of computed positions is determined by the speed of the vehicle and the sampling rate of the receiver.

The primary requirement for an accurate differential kinematic GPS survey is determining the initial carrier phase cycle ambiguity. The phase cycle ambiguity for each satellite is the number of cycles of carrier phase between the reference receiver and the mobile receiver. This ambiguity can be resolved by either indexing or conducting an antenna swap. Indexing refers to starting the survey with both the reference and mobile GPS antennas located on known monuments. The antenna swap technique involves switching the antennas of the reference and mobile receivers at the beginning and end of the survey (REMONDI, 1985). Recently, sophisticated data processing strategies have emerged that allow the user to solve for cycle ambiguity under certain conditions without the requirement for indexing or an antenna swap. Whatever the method, once the initial phase ambiguity is known, the position of the mobile receiver can be determined from the change in the observed carrier phase of the mobile receiver, provided the receivers maintain continuous phase lock on the satellites being tracked.

## EXPERIMENT DESCRIPTION

Field experiments were conducted to evaluate GPS surveying techniques for monitoring beaches, to develop procedures for collecting and analyzing GPS data for coastal applications, and to evaluate the accuracy and potential sources of error of GPS beach surveys. The experiments also provided a means of establishing the minimum manpower, equipment, and sampling parameters (rate and duration) necessary for a successful beach survey, and a way of determining the advantages and disadvantages of GPS surveys compared to other surveying techniques. It was expected that the GPS techniques developed during the pilot project phase could be modified to become a standard field technique for surveying large beach areas, determining volumetric nearshore changes, monitoring movement of significant morphological features, conducting post-storm impact assessments, and establishing ground truth for aerial reconnaissance work.

### Equipment

The GPS geodetic survey equipment employed during the experiments (Figures 3–5) included three battery-powered, 12-channel GPS receivers (two active units and one backup), three bipod range poles with special vehicle mounting brackets, a roof mount for attaching an antenna to the vehicle, a vehicle side mount for transporting the bipod and antenna between locations, and a pad of microwave absorbent material to prevent multipath signal reflection from the roof of the vehicle. The conventional survey equipment consisted of a theodolite and range pole. In order to allow precise reoccupation of transect stations, 20-cm-long aluminum pins were driven into the beach as markers at each station. Each pin was indented with a small (2 mm radius by 2 mm deep) dimple to allow the pointed end of the bipod to reoccupy precisely the same point on the pin (Figure 4).

A 2 km segment of sand beach at Galveston Island State Park was selected as the experiment site. This area is controlled by Park officials and was chosen to mitigate the possibility of interference from unauthorized vehicles, beach scraping, or vandalism. The site was also selected because beach profiles have been surveyed there since 1983 (MORTON and PAINE, 1985). Four beach transects oriented perpendicular to the shore (Figure 1) were established using conventional surveying equipment and a two man crew. Survey stations along each transect were located where beach morphology changed (landward edge of dunes, dune crest, dune toe, vegetation line, berm), or were spaced 5 m apart on the uniformly sloping part of the beach. Each station was marked with a flathead pin driven flush with the beach surface, and the pin and surrounding sand were sprayed with a bright water-based paint for easy identification. Each transect consisted of 11 to 13 stations depending on beach width at high tide (Figure 1). Those station marker pins located immediately seaward of the vegetation line, at the berm, and on the forebeach were also marked with surveying flags (Figure 2) so that they could be spotted from a moving vehicle. Together the dune stations and beach stations formed a network of survey transects from which a beach surface could be constructed.

### GPS Surveys

For the GPS surveys, both the indexing method and the antenna swap method were employed for resolving the initial carrier phase ambiguity. A reference point and an index point were established landward of the dunes located approximately 7 m apart (Figures 1–3). This distance was chosen to allow for convenient antenna swaps. Any reasonable baseline up to approximately 10 km could have been used for the indexing approach. Experience has shown that beyond 10 km the baseline-dependent errors make it difficult to resolve the initial carrier phase ambiguity to the 1-cm-level precision required for this experiment.

GPS surveys were conducted during daylight hours and at times that maximized the number of satellites in view on November 15 (day 319) and 16 (day 320), 1991. As many as seven satellites were tracked simultaneously and no survey was conducted with less than four satellites in view. Although at least four satellites are required to solve for the four unknowns (3-D position and time), collecting data from more than four satellites improves the geometric strength of the solution and provides additional robustness to the data reduction process in the event of satellite shading or change in the satellite scenario.

We conducted both stop-and-go kinematic surveys (Figures 6–8) and fully kinematic surveys (Figures 9–11). Each technique was replicated on consecutive days and one stop-and-go survey was replicated on the same day to test the accuracy

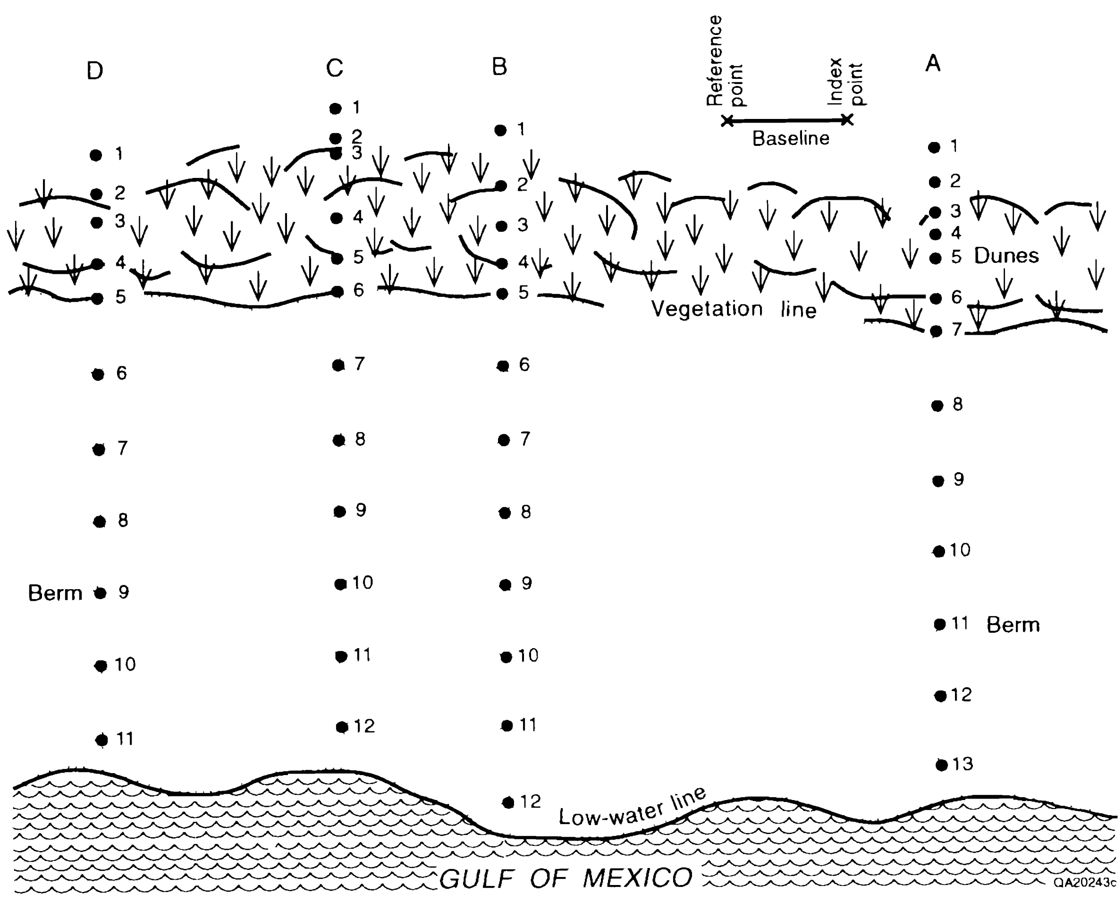


Figure 1. Generalized plan view of beach-profiling transects established using conventional surveying techniques and then replicated using stop-and-go GPS techniques. Survey station numbers and GPS baseline (reference point and index point) are shown generally in relation to beach features. Drawing is not to scale.

and repeatability of GPS surveys under different satellite geometries.

The stop-and-go kinematic surveys involved a field operator, with a GPS receiver carried in a backpack and the GPS antenna mounted on a bipod range pole (Figure 4). The receiver collected data every 6 seconds at fixed stations in rapid succession. The time required to survey a shore-normal transect using stop-and-go techniques varied from 35 to 50 min, including initialization of the receivers at the reference site. This compares favorably with the time required for a typical theodolite survey, which varied from 45 min to 1 hr for each transect, including equipment set up. In general, the time required to conduct stop-and-go GPS surveys depends on the number of transect stations and the duration of data collection at each station.

The fully kinematic technique involved attaching the GPS antenna to a roof-mounted bracket on a vehicle (Figure 5). The vehicle was then driven in a quasi-orthogonal pattern that encompassed both shore-normal and shore-parallel profiles (Figure 2), while collecting GPS data at a one-second rate. During the kinematic survey, the vehicle was stopped when the antenna was over a flag, and positioning data were collected for approximately 2 min. These stationary events were recorded and numbered to signify tie points (flagged stations) that were common to both the shore-parallel and shore-normal profiles. Each shore-normal profile was repeated by driving from

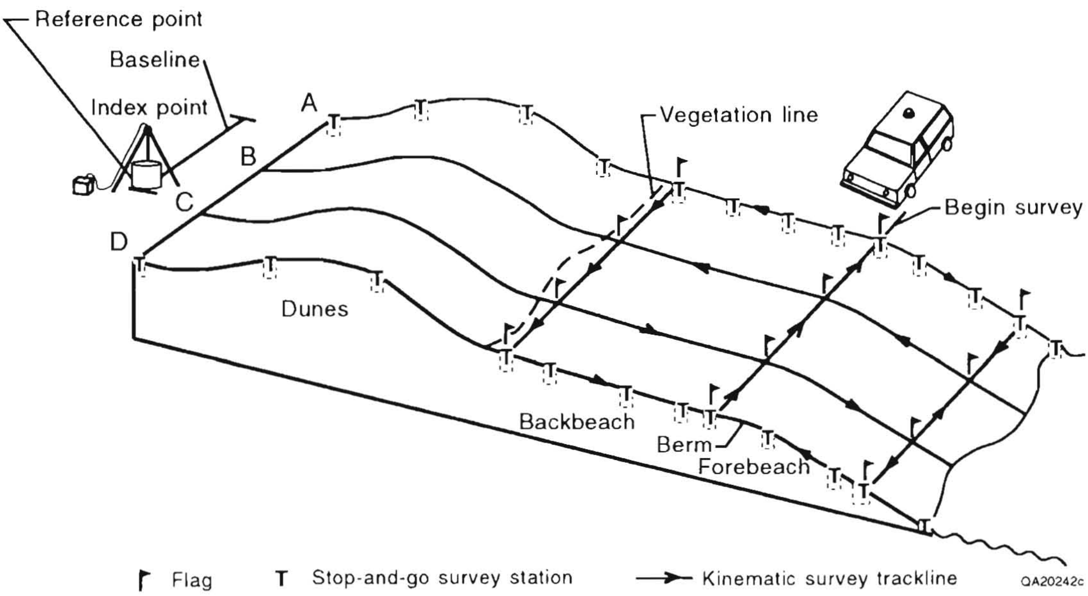


Figure 2. Conceptual layout of Galveston Island State Park test site showing GPS baseline and kinematic surveying tracklines in relation to beach and dune features. The arrows indicate the direction of vehicle movement. Drawing is not to scale.

Figure 3. Configuration of GPS equipment at the reference point and index point of the baseline.

Figure 4. Configuration of GPS equipment during stop-and-go surveys. This procedure is comparable to a conventional land survey whereby static positioning data are collected at discrete stations along a transect.

the water toward the dunes, and then backing down the profile (Figure 10). The kinematic survey on day 319 and its replicate on day 320 each covered slightly more than 6 km of profile data and each was completed in 1.5 hr. This elapsed time included 1 hr of actual driving time (three shore-parallel transects and four shore-normal transects) and 15 min before and after the survey for antenna swaps at the reference site. The kinematic experiments achieved two goals: they tested the accuracy of positions obtained from a moving vehicle, and they linked the shore-normal and shore-parallel profiles so that a more accurate representation of the beach surface could be obtained.

### Experiment Anomalies

During high tide, between GPS surveys on days 319 and 320, as much as 10 cm of sand was locally deposited on the forebeach burying the most seaward pins on shore-normal transects A and B (Figure 1). This cover of sand was removed at the most seaward pins so that replicate stop-and-go surveys measured the same predeposition surface. Locally removing the sand was necessary to test stop-and-go GPS repeatability and to avoid introducing a real change in the beach height. The deposition of sand between GPS surveys also allowed us to test the detection of real beach changes using the fully kinematic surveying technique.

At some beach sites the vehicle weight caused slight sand compaction, depending on the location of the trackline. Hard-packed sand seaward of the berm prevented any significant compaction, whereas the dry sand of the backbeach compacted as much as 2 cm when it was first driven on. However, the lowered elevation caused by sand compaction was within the overall error of the surveys. Some minor differences in the trackline between surveys were caused by the driver's inability to precisely reoccupy tire tracks of the previous kinematic survey.

## DATA ANALYSIS

### GPS Data Reduction

A static GPS survey was conducted prior to the beach monitoring experiment to determine the coordinates for the reference and index sites and to tie these coordinates and the experimental data to the established World Geodetic System of 1984

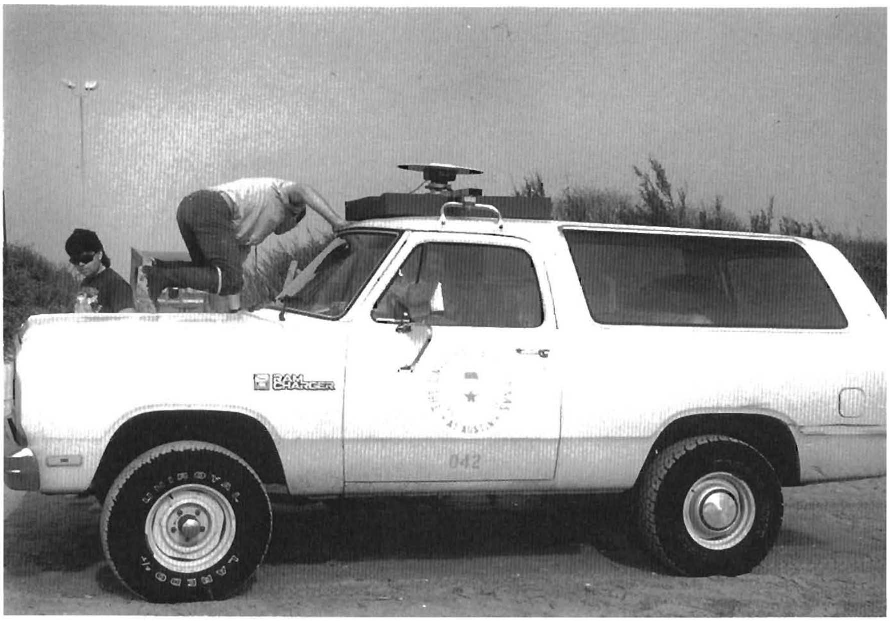

Figure 5. Configuration of GPS equipment during kinematic surveys. This procedure provides continuous positioning of the vehicle (antenna). Density of data across the beach is determined by the vehicle speed and GPS sampling rate.

(WGS 84). Approximately 3 hrs of GPS data were collected at each site and at a permanent GPS Regional Reference Point (RRP) site near Houston (operated by the Texas Department of Transportation; TxDOT). Data from all of these sites were post processed to compute positions using the vendor-supplied software. As described above, the positions are computed relative to a known reference site, in this case the TxDOT RRP. The TxDOT RRP site is part of the National Geodetic Survey (NGS) high-precision network, and thus the reference site, and all of the field survey data, were tied to the NGS high-precision network through this process.

The stop-and-go kinematic survey positions for each transect station were generated using the NGS OMNI kinematic post-processing software. The OMNI software was used to produce a centimeter level position for the roving antenna at every epoch. Averaging of the independent positions was employed to reduce the random error and to produce a single position for each transect station. The vehicle kinematic GPS data were also post-processed using the NGS OMNI software package, producing an independent position for the mobile antenna at every epoch. During times when the vehicle was static over the survey flags, the independent solutions were averaged to produce a single position for the vehicle GPS antenna.

### Plotting of Post-Processed Data

Preliminary editing of the post-processed data was accomplished using plots of ellipsoidal height versus time (Figure 6). When this type of plot is annotated with field notes, it can be used to recognize extraneous values and possible problems with the GPS receivers. At this stage of data reduction, extraneous values can be eliminated and clusters of data at each transect station can be averaged to a single value for plotting on graphs or maps.

GPS vertical positions are reported as heights above the ellipsoid that approximates the geoidal surface (LEICK, 1990). These heights are not elevations above a sea level datum such as the North American Datum of 1983 (NAD 83), but can be related to mean sea-level height with knowledge of the local geoidal height. GPS computed positions were corrected to represent a point on the

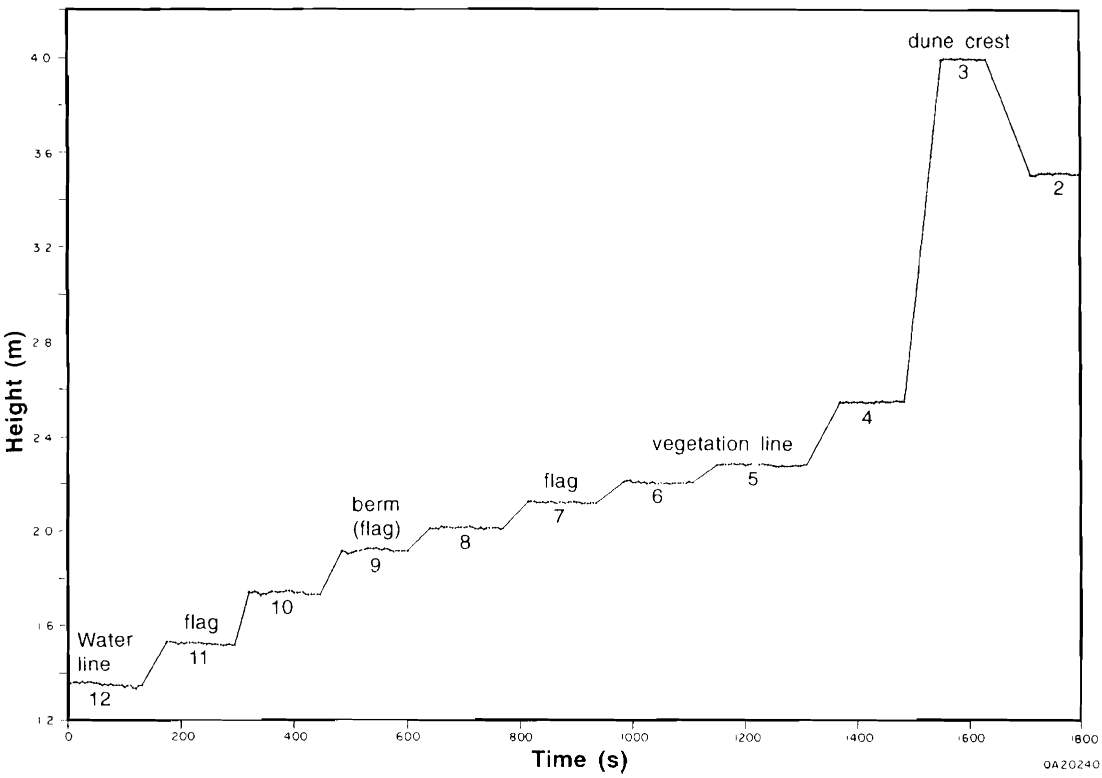


Figure 6. Station height versus time for the GPS stop-and-go survey at transect B on day 319.

ground by subtracting the constant height of the antenna above the beach surface. The antenna-height correction for the stop-and-go survey of transects C and D on day 319 was 1.898 m, and the antenna-height correction for the remaining stop-and-go surveys was 1.893 m. The antenna-height correction for the kinematic surveys was 2.040 m and 2.135 m, on day 319 and day 320, respectively.

A contouring program employing a trend-surface routine was used to generate a beach surface from more than 3,250 data points, most of which were collected from the three shore-parallel transects. Mapping the unedited data revealed two contouring problems. First, clusters of data at tie points in the survey grid caused local "bulls eyes" that were eliminated by averaging static data at the flagged stations. This was accomplished by averaging z (height) values of all data points that do not exceed certain user-specified changes in lateral coordinates (x and y). A 1 m threshold value was used for detecting changes in position. The second contouring problem involved some large anomalies introduced at the ends of the survey due to a lack of data. This end effect is a common difficulty with contouring programs.

## RESULTS

The integrity of a kinematic GPS survey is determined by assessing how closely the initial phase ambiguity is resolved. Ideally, the phase ambiguity will be a whole integer number of carrier phase cycles. In practice, the phase ambiguity should be resolved to within 25% of the correct integer number of cycles, which corresponds to an error of about 5 cm. In all cases for this experiment, resolution of the phase ambiguity was within 2% of the integer value, which represents an error of less than 0.4 mm per satellite. The consistency and accuracy of the kinematic GPS

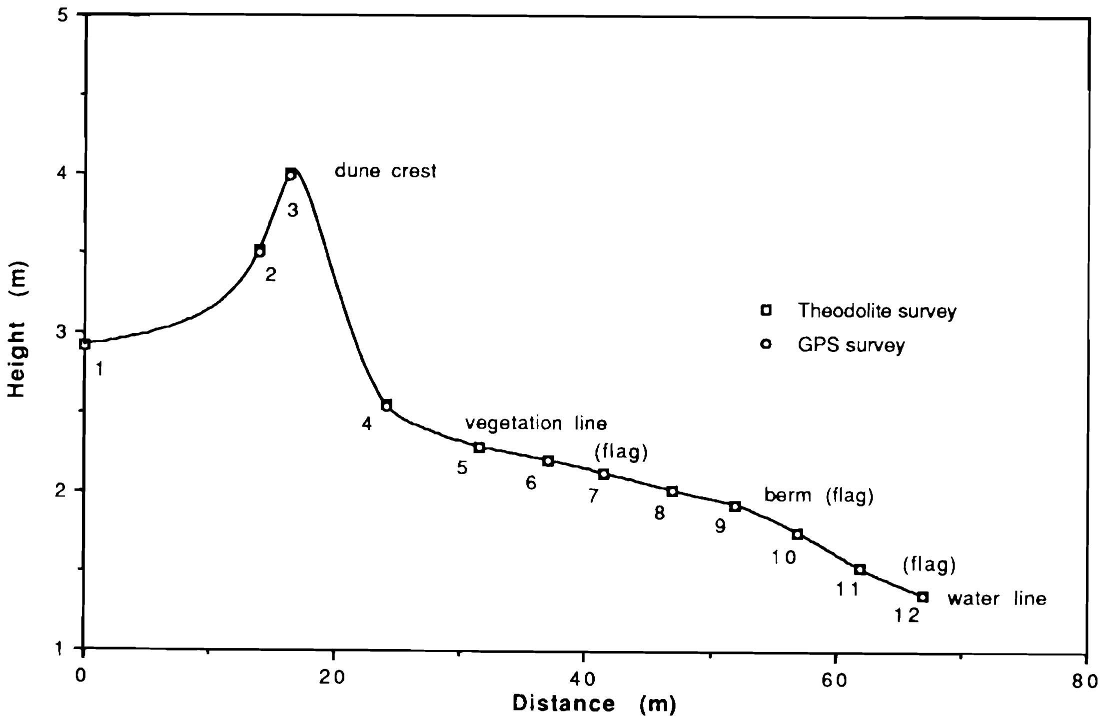


Figure 7. Comparison of beach profiles at transect B obtained using conventional surveying methods and stop-and-go GPS techniques. Symbols are superimposed at each station because heights are essentially the same (Table 1).

surveys (including the stop-and-go survey) can be estimated by examining the magnitude of the closing errors when the mobile GPS antenna is returned to the index point at the end of the survey. Ideally, the closure should be on the order of the measurement noise, typically at the few mm level. In this experiment, the closing errors approached the ideal, with the typical error in each component being less than 0.5 cm.

In order to assess the potential benefit of GPS surveying techniques applied to beach monitoring, two issues are of paramount importance: accuracy and repeatability. To evaluate GPS survey accuracy, comparisons were made between theodolite and GPS stop-and-go measurements. To assess GPS survey repeatability, the stop-and-go and kinematic surveys were repeated on day 320. In addition, the kinematic GPS positions were used to estimate changes in beach erosion and deposition between days 319 and 320. These results are discussed in detail in the following paragraphs.

### Comparison of Theodolite and GPS Surveys

Even after correcting for theodolite and GPS instrument heights, the adjusted heights at each station cannot be compared directly because the theodolite surveys were not referenced to a local bench mark with known elevation. Nevertheless, measured height changes between profile stations can be used to compare the two methods and to search for systematic biases in the data. Beach profiles obtained at transect B on day 320 using both conventional ground surveys and stop-and-go GPS techniques are shown in Figure 7. The superimposed profiles and differences in beach height between stations (Table 1) demonstrate that stop-and-go GPS methods can accurately depict beach surfaces. The differences in beach height measured by the two methods range from 0.1 cm to 1.7 cm (Table 1).

### GPS Repeatability Tests

Repeatability of the stop-and-go GPS method was tested by surveying profile B on day 319 and

Table 1. *Comparison of Δ heights obtained on day 320 at transect B using conventional surveying techniques and stop-and-go GPS techniques.*

| Station Number | Theodolite Height (m) | Δ Height (m) | GPS Height (m) | Δ Height (m) | Difference Δ Height (cm) |
|---|---|---|---|---|---|
| 2 | 3.52 | | 3.493 | | |
| 3 | 4.01 | −0.51 | 3.983 | −0.490 | 0.2 |
| 4 | 2.55 | 1.46 | 2.535 | 1.448 | 1.2 |
| 5 | 2.28 | 0.27 | 2.274 | 0.261 | 0.9 |
| 6 | 2.20 | 0.08 | 2.195 | 0.079 | 0.1 |
| 7 | 2.12 | 0.08 | 2.114 | 0.081 | −0.1 |
| 8 | 2.01 | 0.11 | 1.999 | 0.115 | −0.5 |
| 9 | 1.92 | 0.09 | 1.918 | 0.081 | 0.9 |
| 10 | 1.74 | 0.18 | 1.737 | 0.181 | 0.1 |
| 11 | 1.52 | 0.22 | 1.528 | 0.209 | 1.1 |
| 12 | 1.35 | 0.17 | 1.341 | 0.187 | −1.7 |

Table 2. *Comparison of beach profiles at transect B surveyed using stop-and-go techniques on day 319, on day 320, and repeated on day 320.*

| Station | 319 Height (m) | 320 Height (m) | 319–320 Diff. (cm) | 320 (Rep) Height (m) | 319–320 (Rep) Diff. (cm) | 320–320 (Rep) Diff. (cm) |
|---|---|---|---|---|---|---|
| 2 | 3.505 | 3.493 | 1.2 | — | — | — |
| 3 | 3.993 | 3.983 | 1.0 | 3.985 | 0.8 | −0.2 |
| 4 | 2.542 | 2.535 | 0.7 | 2.524 | 1.8 | 1.1 |
| 5 | 2.278 | 2.274 | 0.4 | 2.259 | 1.9 | 1.5 |
| 6 | 2.203 | 2.195 | 0.8 | 2.180 | 2.3 | 1.5 |
| 7 | 2.120 | 2.114 | 0.6 | 2.093 | 2.7 | 2.1 |
| 8 | 2.012 | 1.999 | 1.3 | 1.988 | 2.4 | 1.1 |
| 9 | 1.917 | 1.918 | −0.1 | 1.908 | 0.9 | 1.0 |
| 10 | 1.737 | 1.737 | 0.0 | 1.718 | 1.9 | 1.9 |
| 11 | 1.524 | 1.528 | −0.4 | 1.516 | 0.8 | 1.2 |
| 12 | 1.351 | 1.341 | 1.0 | 1.350 | 0.1 | −0.9 |

twice on day 320 (Figure 8, Table 2). There is remarkably good agreement among all three stop-and-go surveys with errors in the range of ±2 cm. These repeatability tests indicate that GPS surveys are at least as accurate as theodolite and stadia rod surveys.

The ±2 cm errors are dominated by a bias in the day 320 data with respect to the day 319 data. On day 320, the station marker pins are consistently lower than on day 319 by 1–2 cm. These differences are attributed to depression of the station marker pins caused by reoccupation of the marker with the bipod range pole. Bipods used for the stop-and-go surveys have a vertical leg that is pointed at the lower end for precise positioning (Figure 4). This design concentrates the weight of the antenna on the vertical leg, causing a slight depression of dry sand at a few stations in the back beach and dunes.

The post-processed vehicle kinematic data were compared both analytically and visually to assess how much of the mapped difference was due to vagaries of the contouring software and how much was due to actual changes in the beach surface. Comparison of the shore-parallel transects revealed nearly identical values along the stable backbeach and close agreement for the berm and forebeach transects (Figure 9). The alongshore kinematic surveys also illustrate height changes and rhythmic topography along the backbeach, berm, and forebeach. Agreement between the two surveys is extremely good, especially where the backbeach was stable and the trackline was reoccupied. This one-dimensional comparison shows that at least along the tracklines, the fully kinematic surveys can be replicated at the centimeter scale of accuracy.

The sand deposited at high tide between GPS surveys on days 319 and 320 also influenced the kinematic surveys. It was impractical to remove the high-tide sand deposit from the entire forebeach so a true change in beach height was included in the foreshore transect of day 320. At the most seaward stations on shore-normal transects, the forebeach height increased about 9 to 10 cm as a result of the sand deposition (Figure 10).

### Beach Surface Integration Using Kinematic GPS Positions

The entire beach surface between the water line and the dune line was integrated using kinematic GPS post-processed positions. Maps of the kinematic surveys on days 319 (Figure 11) and 320 accurately depict general morphological features of the beach surface, such as a steeper forebeach and more gently sloping backbeach. Furthermore, these maps accurately portray beach slopes and an increase in backbeach elevation from 2.1 to 2.2 m in a southwesterly direction. The data were contoured using several different algorithms and two different contouring programs to investigate the differences in surfaces attributable to software. Gridding was also altered to determine the sensitivity of parameter selection. Additional work is needed to determine which contouring routines provide the most accurate spatial representation of the data while introducing the least error at-

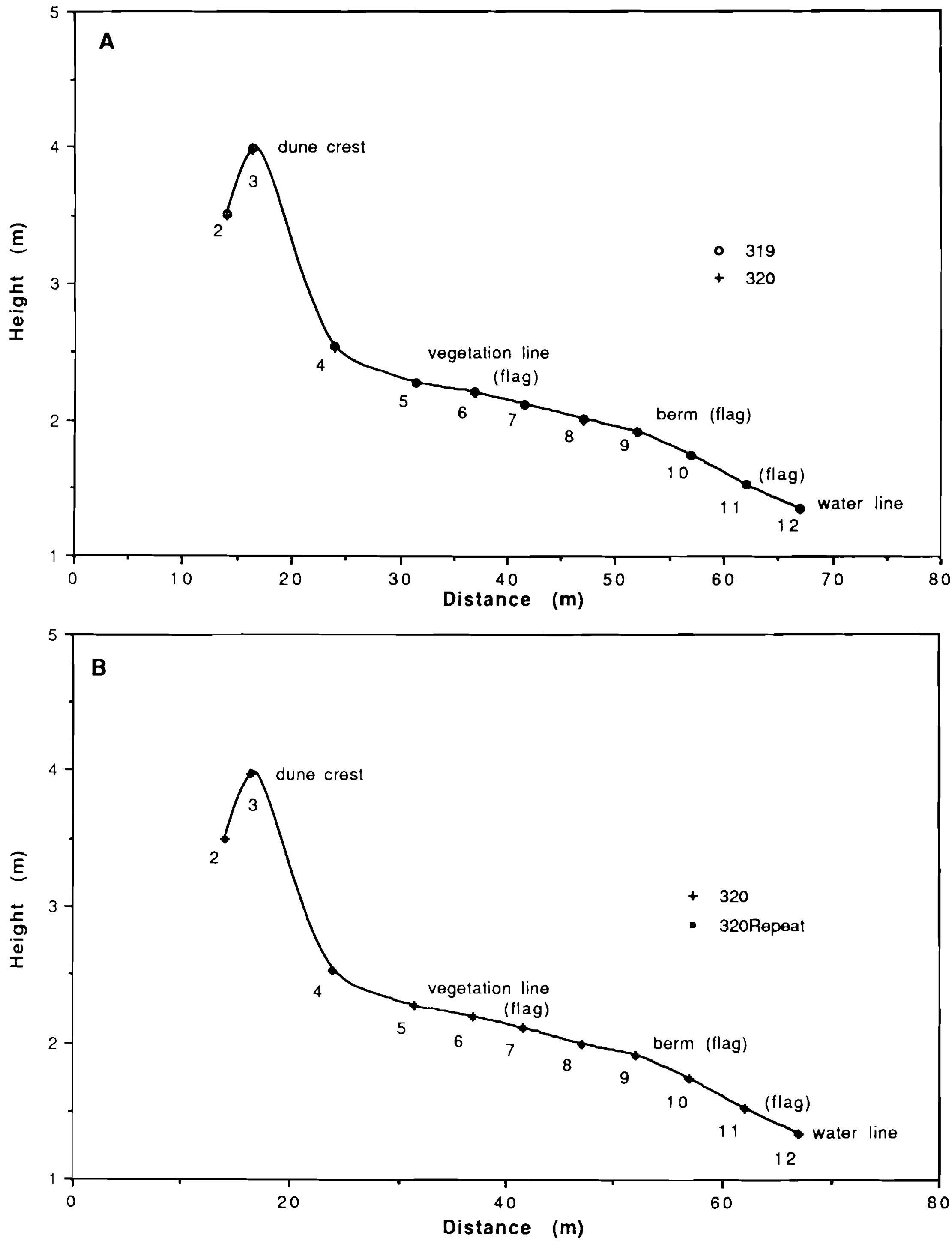


Figure 8. Repeatability of GPS stop-and-go surveys conducted (A) on consecutive days (319 and 320) and (B) on the same day (320). Symbols are superimposed at each station because heights are essentially the same (Table 1).

(a)

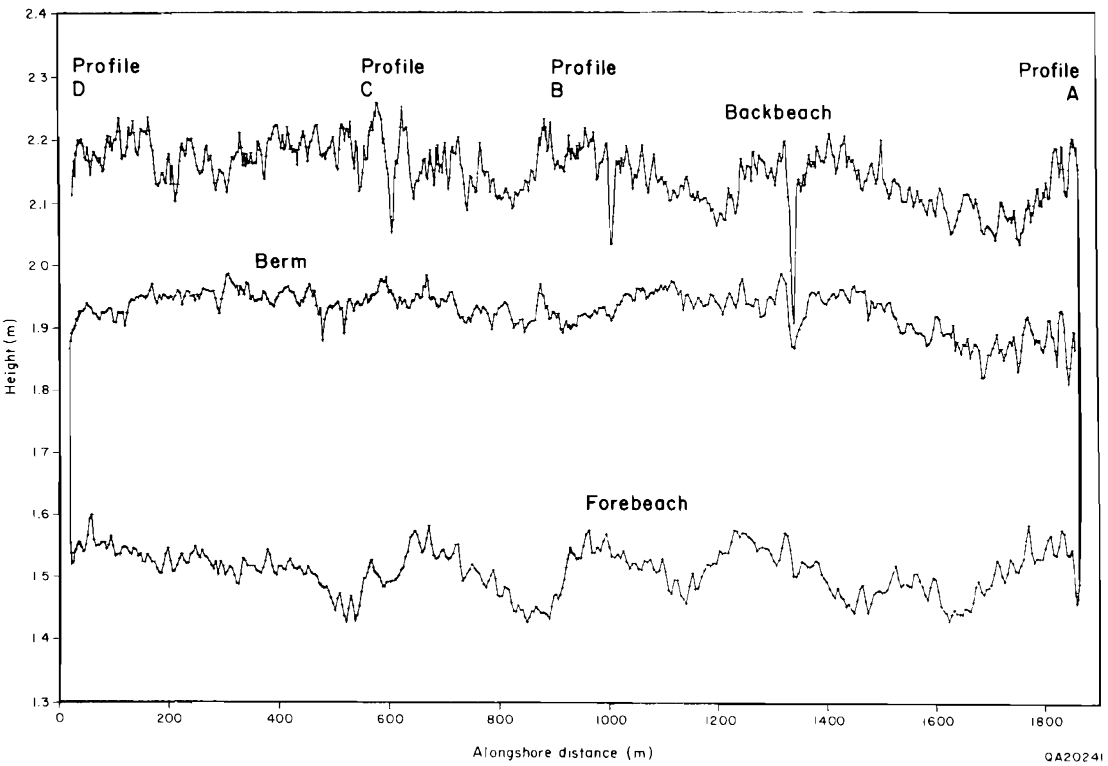


Figure 9. Alongshore plots of kinematic GPS surveys showing repeatability of height versus range measurements on (A) day 319 and (B) day 320.

tributable to the gridded values generated by the software.

Height differences between beach surfaces were computed to evaluate repeatability of kinematic GPS surveys on days 319 and 320 (Figure 12). Ignoring the obvious end effects, the largest errors are located between the shore-parallel transects where no data were collected. The isolated, unexplained apparent differences in beach surfaces illustrated by the map are probably caused by contouring algorithms and the creation of data points for a predetermined grid.

Table 3. *Differences in beach surfaces constructed from kinematic GPS surveys on days 319 and 320.*

| | Volumetric Difference ($m^3$) | Normalized for Beach Area (cm) | Normalized for Beach Length ($m^3$/m) |
|---|---|---|---|
| Positive change | +511.7 | | |
| Negative change | −589.1 | | |
| Gross change | 1,100.8 | 1.100 | 0.550 |
| Net change | −77.4 | 0.077 | 0.038 |

The minimum volumetric change that can be detected when conducting subsequent kinematic surveys of the same area was estimated by comparing apparent height differences in beach surfaces between days 319 and 320. This error analysis includes volume estimates for both absolute and net differences in measured beach heights (Table 3). The absolute volume of both positive and negative differences is about 1,100 $m^3$. This volume is equivalent to 0.55 $m^3$/m of beach or an average height difference of 1.1 cm for the entire length of beach surveyed (Table 3). The net volume difference between days 319 and 320 is approximately 77.4 $m^3$, which equates to 0.038 $m^3$/m or an average height error of 0.077 cm across the surveyed beach.

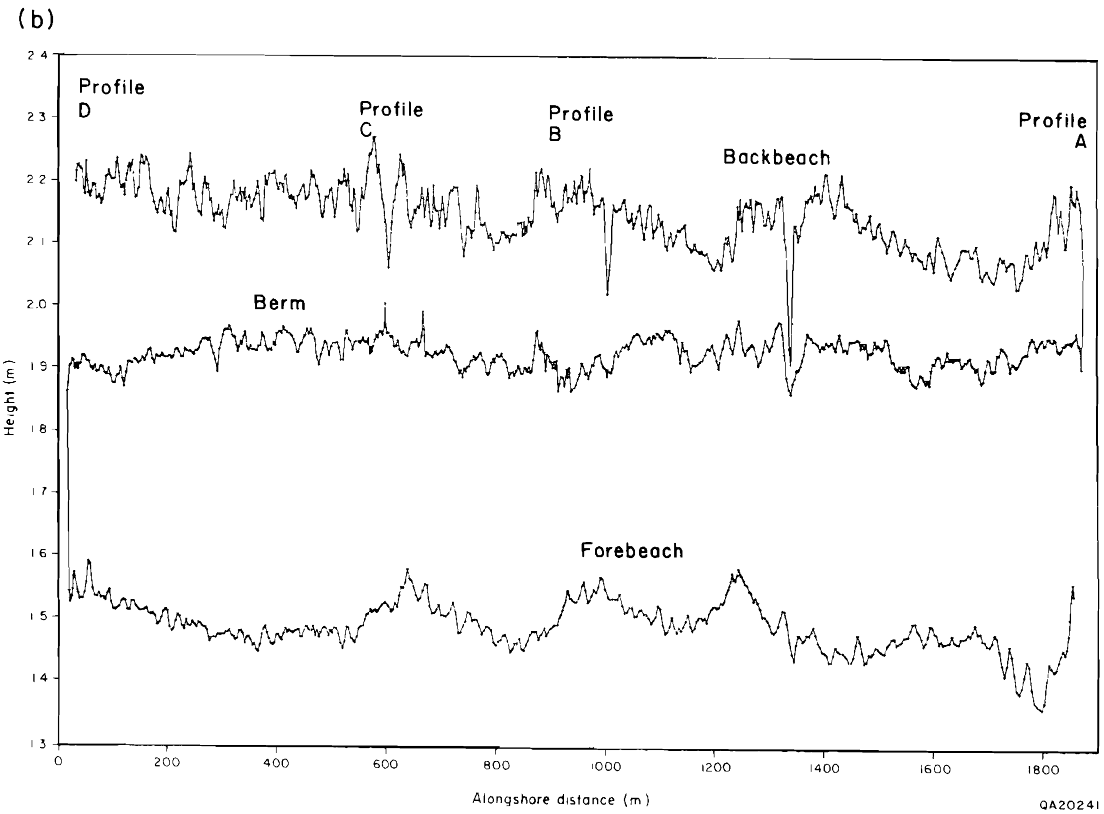


Figure 9B.

## DISCUSSION

### GPS Applications

Beaches are nearly ideal environments for conducting GPS surveys because the unobstructed horizontal field of view generally circumscribes a 180° arc and some undeveloped coasts provide unobstructed views of 360°. GPS surveys may not be practical along some developed coasts where tall, closely spaced buildings may interfere with the satellite signals. Isolated structures near the beach may cause minor shading or cycle slips, whereas dense, high-rise structures may entirely block the signal from satellites near the horizon or cause multipath reflections severe enough to invalidate the surveys.

Shore-parallel profiles (Figure 9) literally add a new dimension to beach monitoring that reveals alongshore morphological variability and suggests sediment transport directions. In the field, the beach surface appeared to be planar, but kinematic GPS surveys revealed that it is slightly undulatory alongshore. As expected, the low-relief rhythmic topography is most pronounced along the forebeach and is present along the backbeach, but is poorly expressed along the berm. Rhythmic topography of the forebeach has wavelengths of about 90 m, whereas the features are spaced about 120 to 150 m apart along the backbeach (Figure 9). The backbeach topography is enhanced by water ponding and runoff after heavy rains. Water draining from the backbeach to the Gulf of Mexico carves small narrow gullies that transect the berm and are obliterated by sediment movement on the forebeach. Shore-parallel beach profiles may be even more important than shore-normal profiles for monitoring beach shapes and elevation changes and their relationship to seasonal cyclicity, storm processes, and post-storm recovery. Parallel efforts are being conducted by the

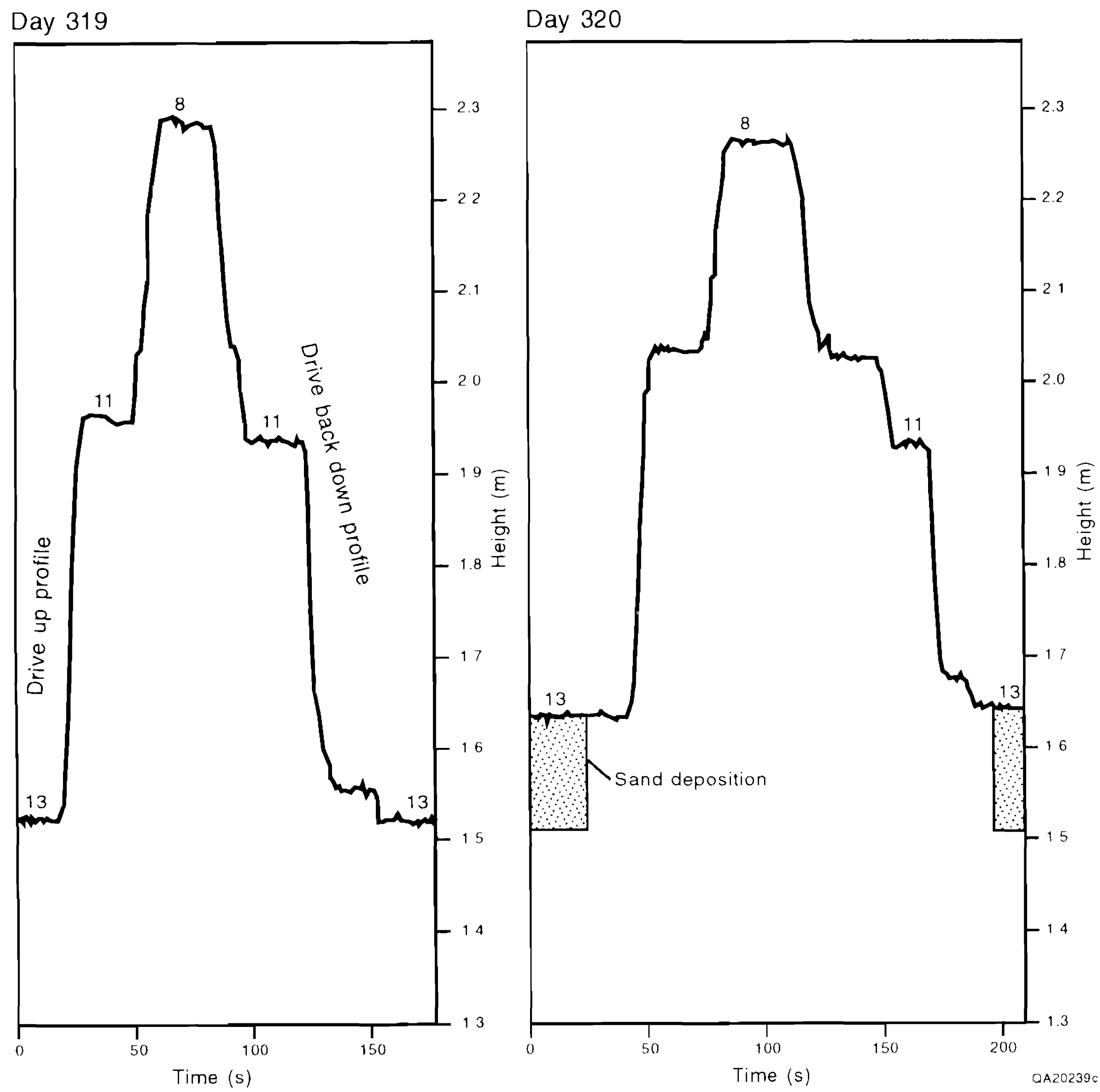


Figure 10. Shore-normal kinematic GPS surveys at transect A on day 319 and day 320. Numbers on each profile refer to survey stations shown on Figure 1. Comparison of the two profiles shows 9 to 10 cm of increased height at station 13 on day 320 attributed to high-tide sand deposition.

U.S. Army Corps of Engineers and U.S. Geological Survey to link GPS positioning with airborne laser and sea-based bathymetric surveys to monitor changes across the shoreface and in shallow water on the continental shelf.

Kinematic beach surveys are restricted to beaches where vehicular access is both possible and practical. Another limitation of a vehicular survey is that it excludes the dunes or densely vegetated upland areas adjacent to the beach. Driving in the dunes is both illegal and impractical, and upland areas are commonly private property. Nevertheless, including dunes and vegetated uplands into the survey is critical for analyzing beach dynamics because they commonly represent both sand sinks (dunes, washover fans,

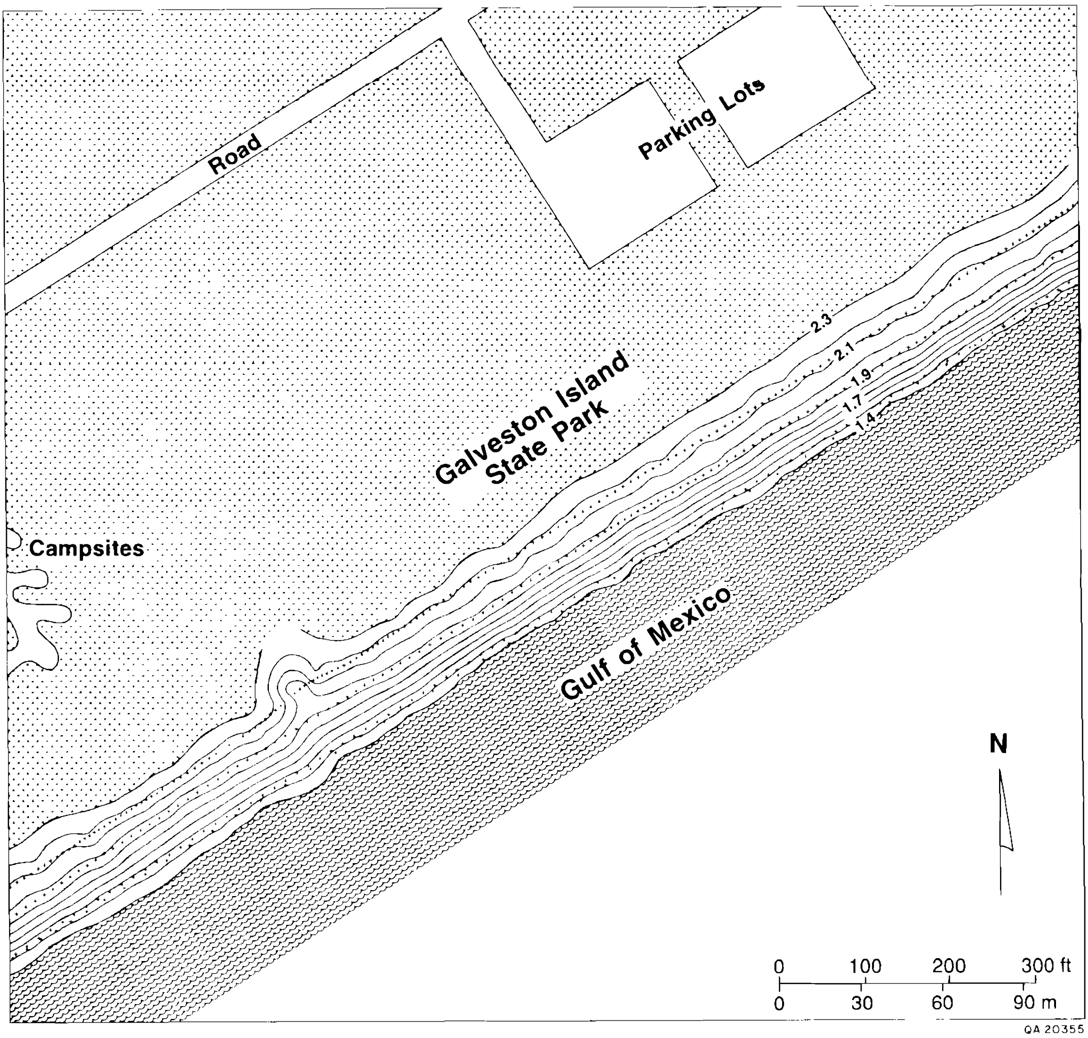


Figure 11. Representative segment of the beach surface contoured by integrating x, y, and z coordinate data for the kinematic GPS survey on day 319. Contour interval is 0.1 m.

and storm terraces) and sand sources (nearshore erosion) and therefore are an integral part of the beach system. This limitation in data acquisition can be overcome by conducting stop-and-go surveys in areas that cannot be reached by driving and using control points in the backbeach to link the stop-and-go and kinematic surveys (Figure 2). Data generated by both techniques would be compatible by the very nature of GPS data since all the positions are referenced to the WGS 84 ellipsoid.

## Comparison of Conventional and GPS Beach Surveying Systems

Conventional and GPS surveying systems were evaluated on the basis of system performance including accuracy, repeatability, total cost, efficiency of operation, and support requirements (Table 4). Accuracy and repeatability of the two techniques were addressed in the preceding sections.

Both techniques utilize durable field equip-

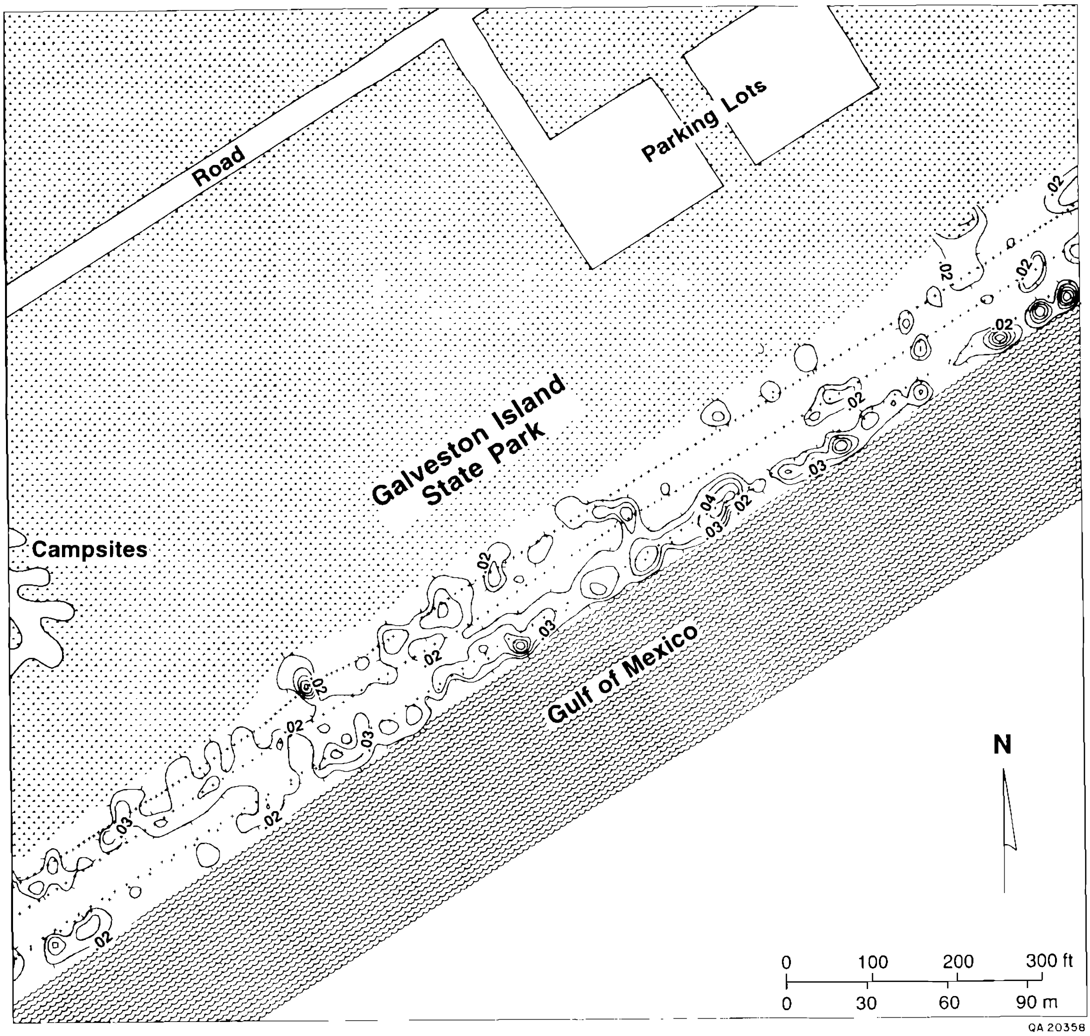


Figure 12. Representative segment of residual differences between beach surfaces surveyed using kinematic GPS techniques on days 319 and 320. Systematic positive values seaward of the berm represent forebeach deposition during high tide. Contour interval is 0.01 m.

ment that can be easily transported, assembled, and maintained. Stored power is a minor inconvenience of GPS equipment (and electronic surveying equipment), especially at remote locations where battery recharging facilities may not be available. The theodolite surveys averaged about 1 hr per profile, including time spent installing the pins and marking each station. Past experience has indicated this is a reasonable time estimate for most beach profiles and the additional time required to install the pins (10–15 min) did not add significantly to the total time of the survey. Most of the elapsed time is related to equipment set-up for the theodolite and indexing of the GPS receivers.

Costs of GPS beach surveys may be substantially greater than conventional surveys because the highest accuracy requires two GPS receivers operating simultaneously. However, considering the rapid evolution in electronic equipment, it is likely that future GPS receivers will cost less, use less power, be more compact, have more data stor-

Table 4. *Comparison of advantages and disadvantages of conventional and GPS beach surveys.*

| Attributes | Conventional Beach Surveys | GPS Beach Surveys |
|---|---|---|
| Field equipment | Portable, relatively inexpensive if non-electronic | Portable, moderately expensive; two multi-channel receivers operating in differential mode are necessary for high precision |
| Power requirements | None if non-electronic† | Battery operated; recharging may be necessary for lengthy surveys |
| Spatial limitations | Line-of-sight between instrument and rod or reflecting prism | Line-of-sight between satellite and receiver; obstructions can block signal, cause shading, or create multipaths |
| Reference station | None required | Must be within 10 km of survey for high precision |
| Operational mode(s) | Static only† | Static or dynamic |
| Areal coverage | Discrete locations only† | Discrete or continuous locations |
| Positioning | Relative heights unless starting from a known elevation; no geographic locations (latitude and longitude) | Absolute three-dimensional position (height, latitude, longitude) obtained after post-processing |
| Data format | Visual observations and manual records† | Digital signals and digital records stored in receiver |
| Data storage and transfer | Hand-written notes, computer transfer and manipulation requires data entry† | Digital records stored in receiver; directly downloads to computer |
| Data reduction | Tables or simple trigonometric calculations† | Complex equations requiring post-processing software |
| GIS compatibility | Requires data entry† | Fully compatible transfer |
| Training requirements | Minimal training required, vendor manuals normally are adequate | Moderate training required; exceeds instructions provided by vendor manuals |

†Autotracking total stations with electronic notebooks are expensive but they have digital data capabilities that are similar to those of GPS receivers

age capacity, and perform more functions than those that are currently on the market. Potential additional field costs arise from the need to have a third person to protect the equipment at the reference station if the equipment can not be placed in a secure, weatherproof environment. Some electronic surveying equipment can automatically track the reflecting prism, but these total stations cost more than a geodetic-quality GPS receiver.

To evaluate efficiencies of conventional beach surveying compared to GPS surveying, we examined both field operations and data analysis. Considering both aspects, GPS surveying systems have a distinct advantage over conventional surveys for several reasons. First, kinematic GPS positioning is a rapid and efficient beach surveying technique for long beach segments that cannot be matched with discrete, static records collected by conventional surveys or total stations. Second, each GPS receiver provides a user interface that allows for direct downloading of data to a computer for processing and incorporation into a GIS. Total stations with electronic notebooks offer this same advantage, but non-electronic methods do not. GPS data are electronically recorded, stored, analyzed, and displayed, which is a marked improvement over conventional surveys that employ visual observations and manual records that require laborious encoding to prepare the data for computer analysis. It should be noted, however, that detailed descriptions of beach features and changes in surveying operations are essential to properly edit and analyze GPS data. In retrospect, a portable tape recorder would have been an ideal way to register the timing of significant events so that manual entry of notes would have been unnecessary.

Technological advancements such as GPS typically require special training to operate new equipment and to properly analyze the data. Although these requirements are more rigorous for GPS surveys than for conventional non-electronic surveys, the GPS surveys are judged to be superior to conventional beach surveys because they can be conducted in a fully kinematic mode and can provide absolute positioning in three dimensions rather than relative positions in two dimensions. There are autotracking total stations that can be used for limited shore-parallel kinematic surveys, but they are not available to most coastal researchers. Furthermore, the popular manual tracking total stations are incapable of performing kinematic surveys over long beach segments. If shore-normal transects are the only surveying objective, then total stations are more rapid and efficient than either the stop-and-go or fully kinematic GPS surveys. However, if recording the total beach surface is the primary objective, then fully kinematic GPS surveys have a distinct advantage over conventional surveys including total stations.

In summary, both conventional and GPS surveying systems have advantages and disadvantages; however, GPS surveys are superior to conventional surveys for most coastal applications (Table 4). This is because kinematic GPS surveys provide a continuous stream of highly accurate coordinates at speeds that allow rapid surveying of long uninterrupted beach segments without the need for permanent surveying monuments. The ability of GPS to determine absolute geographic coordinates and elevations without fixed monuments means that post-storm surveys can be conducted even where beach erosion has been so great that permanent monuments were destroyed. The main obstructions to kinematic beach surveys after storms would be the rubble from destroyed buildings and failed seawalls in heavily developed areas.

## CONCLUSIONS

GPS surveys are suitable for the next generation of beach profiling techniques because of their superb positioning capabilities and greater utility compared to other available techniques. One-dimensional GPS surveys can provide rapid, moderately inexpensive monitoring of the berm, high-water line, or vegetation line where determining elevation is less important than establishing geographic position. Even more powerful are two-dimensional kinematic surveys that provide rapid synoptic measurement of shoreline indicators and the beach surface between the water line and vegetation line. Comparing surfaces generated by subsequent surveys of the same beach segment yields a three-dimensional (volumetric) representation of gains (deposition) and losses (erosion), thus improving the accuracy of pre- and post-storm beach surveys. Real-time navigation during subsequent surveys of the same beach segment would allow reoccupation of the same tracklines and improve the accuracy of repeated surveys.

Kinematic GPS surveys conducted with an off-road vehicle do not include the dunes and upland areas, which are essential to calculate total volume changes and to estimate sediment budgets. This deficiency can be overcome by combining intermediately spaced stop-and-go surveys of upland areas with kinematic surveys of the beach and upper shoreface. Consequently, GPS surveying techniques will likely replace conventional profiling as the preferred method of monitoring beach changes in the future.

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